# Resonant production of the fourth family slepton at the LHC

O. Çakır* and S. Kuday†

*Department of Physics, Ankara University,*

*Faculty of Sciences, Ankara, Turkey*

İ.T. Çakır‡

*Department of Physics, CERN, Geneva, Switzerland*

S. Sultansoy§

*Physics Division, TOBB University of Economics and Technology, Ankara, Turkey and*

*Institute of Physics, Academy of Sciences, Baku, Azerbaijan*

## Abstract

The resonant production of the fourth family slepton $\tilde{l}_4$ via R-parity violating interactions of supersymmetry at the Large Hadron Collider has been investigated. We study the decay mode of $\tilde{l}_4$ into the fourth family neutrino $\nu_4$ and $W$ boson. The signal will be a like-sign dimuon and dijet if the fourth family neutrino has Majorana nature. We discuss the constraints on the R-parity violating couplings $\lambda$ and $\lambda'$ of the fourth family charged slepton at the LHC with the center of mass energies of 7, 10 and 14 TeV.

*Electronic address: ocakir@science.ankara.edu.tr

†Electronic address: kuday@science.ankara.edu.tr

‡Electronic address: tcakir@mail.cern.ch

§Electronic address: ssultansoy@etu.edu.tr

Existence of the fourth family follows from the basics of the standard model (SM) and actual mass spectrum of third family fermions (see [1] and references therein). Recent studies [2–11] on the allowed parameter space for the fourth family fermions from precision electroweak data show that this space is large enough. The experimental limits on the masses of the fourth family quarks from Collider Detector at Fermilab (CDF) are: $m_{u_4} > 335$ GeV at 95% CL. [12], $m_{d_4} > 338$ GeV at 95% CL. [13]. There are also limits on the masses of the fourth family leptons [14]: $m_{l_4} > 100$ GeV, $m_{\nu_4} > 90$ (80) GeV for Dirac (Majorana) neutrinos. On the other hand, the partial wave unitarity leads to an upper bound 700 GeV for fourth SM family fermion masses [15].

Obviously, if the fourth SM family exists in nature then the minimal supersymmetric standart model (MSSM) should be enlarged to include fourth family superpartners. The inclusion of the fourth SM family into MSSM is straightforward [16] (we denote minimal supersymmetric standart model with three and four families as MSSM3 and MSSM4, respectively). A search for supersymmetry (SUSY) is significant part of the physics program of TeV scale colliders. As mentioned in [17], it is difficult to differentiate MSSM3 and MSSM4 at hadron colliders, because the light superpartners of the third and fourth family quarks has almost the same decay chains if the $R$-parity is conserved. For this reason the pair production of fourth family charged sleptons at future $e^+e^-$ colliders has been proposed in [17] to differentiate the MSSM with three and four families.

The R-parity is defined as $R = (-1)^{3(B-L)-2S}$, where $B$, $L$ and $S$ are the baryon number, lepton number and spin, respectively. It is a useful assignment for the phenomenology, because all the SM particles and Higgs boson have even R-parity, while all the sfermions, gauginos and Higgsinos of the supersymmetry have odd R-parity. The rich phenomenology of the MSSM becomes even richer if R-parity is violated (see [18] and references therein). Concerning MSSM4, R-parity violation (RPV) could provide opportunity to differentiate MSSM3 and MSSM4 at hadron colliders.

The R-parity violating part of the MSSM superpotential is given by

$$W_{RPV} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c \tag{1}$$

where $L(E)$ is an $SU(2)$ doublet (singlet) lepton superfield and $Q(U, D)$ is (are) an $SU(2)$ doublet (singlet) quark superfield(s), and indices $i, j, k$ denote flavour. The coefficients $\lambda_{ijk}$ and $\lambda''_{ijk}$ corresponds to the lepton number violating and baryon number violating couplings,

respectively. The second term in Eq. 1 allows the resonance production of sleptons at hadron colliders.

In this work, we consider the resonant production of fourth family slepton via the process $pp \to \tilde{l}_4^{\,+} X \to \nu_4 \mu^+ X$ and followed by the decay $\nu_4 \to W^- \mu^+$ for the Majorana nature of neutrino at the Large Hadron Collider (LHC) with $\sqrt{s} = 7$, 10 and 14 TeV. Assuming that $W$-boson decays hadronically, the signal will be seen in detector as $\mu^+\mu^+ jj$.

The RPV supersymmetric trilinear interaction terms for the charged fourth family slepton can be written as

$$L_{RPV} = \lambda_{i4k}\tilde{l}_{4L}\bar{l}_{kR}\nu_i + \lambda_{ij4}\tilde{l}^*_{4R}\bar{\nu}^c_i l_{jL} - \lambda_{4jk}\tilde{l}_{4L}\bar{l}_{kR}\nu_j - \lambda_{ij4}\tilde{l}^*_{4R}\bar{\nu}^c_j l_{iL} - \lambda'_{4jk}\tilde{l}_{4L}\bar{q}_{kR}q_{jL} + h.c. \quad (2)$$

where $\tilde{l}_{4L(R)}$ is the fourth family slepton field, $q_{L(R)}$ is the left-handed (right-handed) quark field, and indices $i, j, k$ denote flavour.

The mass matrix of the fourth family charged sleptons in the $(\tilde{l}_{4L}, \tilde{l}_{4R})$ basis is given by

$$M^2_{\tilde{l}_4} = \begin{pmatrix} m^2_{\tilde{l}_{4L}} & a_{l_4} m_{l_4} \\ a_{l_4} m_{l_4} & m^2_{\tilde{l}_{4R}} \end{pmatrix} \quad (3)$$

where $m^2_{\tilde{l}_{4L}} = M^2_{\tilde{L}_4} + m^2_{l_4} - m^2_Z \cos 2\beta(\frac{1}{2} - \sin^2\theta_W)$; $m^2_{\tilde{l}_{4R}} = M^2_{\tilde{E}_4} + m^2_{l_4} - m^2_Z \cos 2\beta \sin^2\theta_W$; $a_{l_4} = A_{l_4} - \mu\tan\beta$, and $A_{l_4}$ is the Higgs-fourth family charged lepton trilinear parameter (the notation of [19] is used).

The mass eigenstates $\tilde{l}_{4l}$ and $\tilde{l}_{4h}$ are related to $\tilde{l}_{4L}$ and $\tilde{l}_{4R}$ by

$$\begin{pmatrix} \tilde{l}_{4l} \\ \tilde{l}_{4h} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{l}_4} & \sin\theta_{\tilde{l}_4} \\ -\sin\theta_{\tilde{l}_4} & \cos\theta_{\tilde{l}_4} \end{pmatrix} \begin{pmatrix} \tilde{l}_{4L} \\ \tilde{l}_{4R} \end{pmatrix} \quad (4)$$

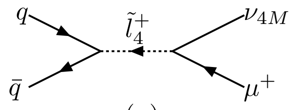
with the eigenvalues

$$m^2_{\tilde{l}_{4(l,h)}} = \frac{1}{2}(m^2_{\tilde{l}_{4L}} + m^2_{\tilde{l}_{4R}}) \mp \frac{1}{2}\sqrt{(m^2_{\tilde{l}_{4L}} - m^2_{\tilde{l}_{4R}})^2 + 4a^2_{l_4} m^2_{l_4}} \quad (5)$$

and the mixing angle $\theta_{\tilde{l}_4}$ is given by

$$\cos\theta_{\tilde{l}_4} = \frac{-a_{l_4} m_{l_4}}{\sqrt{(m^2_{\tilde{l}_{4L}} - m^2_{\tilde{l}_{4l}})^2 + a^2_{l_4} m^2_{l_4}}} \quad (6)$$

As seen from Eq. (5), $\tilde{l}_{4l}$ is expected to be the lightest charged slepton because of large value of $m_{l_4}$.



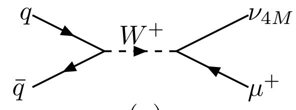




Figure 1: Feynman diagrams of subprocess $q\bar{q}' \to \nu_4\mu^+$: (a) Signal (b) Background

The hadronic cross section for the process $pp \to \tilde{l}_{4l}^+ X \to \mu^+ \bar{\nu} X$ is defined by

$$\sigma = \sum_{i,j} \int \int dx_1 dx_2 \hat{\sigma}_{part}(x_1 x_2 s)[f_i(x_1, Q^2) f_j(x_2, Q^2) + f_i(x_2, Q^2) f_j(x_1, Q^2)] \tag{7}$$

where $x_1$ and $x_2$ are the fractions of parton momentum to proton momentum for two proton beams, $s$ is the square of the center of mass energy, and $Q$ is the factorization scale. For the subprocess shown in Fig.1(a), the partonic cross section $\hat{\sigma}_{part}(\hat{s})$ is calculated as

$$\hat{\sigma}_{part}(\hat{s}) = \sum_{jk} \frac{C_F(\lambda'^{eff}_{4jk}\lambda^{eff}_{442})^2(\hat{s} - m^2_{\nu_4})^2}{16\pi\hat{s}[(\hat{s} - m^2_{\tilde{l}_4})^2 + m^2_{\tilde{l}_4}\Gamma^2_{\tilde{l}_4})]} \tag{8}$$

where $m_{\tilde{l}_4}$and $m_{\nu_4}$ are the masses of fourth family charged slepton and fourth family neutrino, respectively; $C_F$ is the color factor, and the effective couplings are defined as $\lambda^{eff}(\lambda'^{eff}) = \cos\theta_{\tilde{l}_4}\lambda(\lambda')$.

For numerical calculations we implement the vertices from interaction Lagrangian (Eq. 2) into CompHEP [20] with the CTEQ6M [21] parton distribution functions. Masses of the fourth family (Majorano) neutrino and charged lepton are taken as $m_{\nu_4} = 100$ GeV and $m_{\tilde{l}_4} = 300$ GeV, respectively. It should be noted that the main background for our signal, namely $\mu^+\mu^+jj$, will come from the fourth SM family itself (see Fig. 2(b)). This background is proportinal to $|U_{\nu_4\mu}|^2$ . Recent analysis of PMNS matrix elements in the presence of a fourth generation showed that $|U_{\nu_4\mu}| < 0.115$[22].

The signal cross sections at LHC with $\sqrt{s} = 7$, 10 and 14 TeV are given in Tables I, II and III, respectively. In numerical calculations, we assume $\lambda^{eff}_{442}$=0.05, in columns 2-7 corresponding $\lambda'^{eff}_{4jk}$ is equal to 0.05 and remaining ones are zero, in the last columns all $\lambda'^{eff}_{4jk}$ s are equal to 0.05. Using $|U_{\nu_4\mu}| = 0.05$ and $m_{\nu_4} = 100$ GeV, we also calculate the background cross sections as 0.016, 0.024 and 0.035 pb for LHC with $\sqrt{s} = 7$, 10 and 14 TeV, respectively. We use the branching ratio $BR(\nu_4 \to \mu^+W^-) = 0.34$ which is predicted within the parametrization [23] compatible with the experimental data on the masses and mixings

Table I: Cross sections and significance depending on effective RPV couplings at $\sqrt{s} = 7$ TeV with $L_{int} = 1\ fb^{-1}$

| | $\lambda'^{eff}_{411}$ | $\lambda'^{eff}_{412}$ | $\lambda'^{eff}_{421}$ | $\lambda'^{eff}_{413}$ | $\lambda'^{eff}_{422}$ | $\lambda'^{eff}_{423}$ | $\lambda'^{eff}_{4jk}$ |
|---|---|---|---|---|---|---|---|
| $\sigma_S(pb)$ | 0.15 | 0.11 | 0.02 | 0.06 | 9.3x$10^{-3}$ | 3.9x$10^{-3}$ | 0.35 |
| $S/\sqrt{B}$ | 22 | 16 | 3 | 8.8 | 1.4 | 0.6 | 52 |
| $L_{int}(pb^{-1})$ for $3\sigma$ | 18.8 | 35 | 1x$10^3$ | 120 | 5x$10^3$ | 2.8x$10^4$ | 3.4 |

Table II: The same as for Table 2 but for $\sqrt{s} = 10$ TeV and $L_{int} = 100\ fb^{-1}$

| | $\lambda'^{eff}_{411}$ | $\lambda'^{eff}_{412}$ | $\lambda'^{eff}_{421}$ | $\lambda'^{eff}_{413}$ | $\lambda'^{eff}_{422}$ | $\lambda'^{eff}_{423}$ | $\lambda'^{eff}_{4jk}$ |
|---|---|---|---|---|---|---|---|
| $\sigma_S(pb)$ | 0.24 | 0.19 | 0.033 | 0.11 | 0.021 | 9.6x$10^{-3}$ | 0.6 |
| $S/\sqrt{B}$ | 287 | 225 | 38.7 | 130 | 25.2 | 11.4 | 716 |
| $L_{int}(pb^{-1})$ for $3\sigma$ | 11 | 17.8 | 6x$10^2$ | 53.4 | 1.4x$10^3$ | 6.9x$10^3$ | 1.753 |

in the leptonic sector. In the last two rows of Table I, II and III, we present the statistical significance for the signal observations and required integrated luminosity for reaching $3\sigma$.

In figures 2, 3 and 4 we plot integrated luminosity needed for $3\sigma$ significance reach depending on $\lambda'^{eff}_{4jk} \equiv \lambda'^{eff}$ for three different values of $|U_{\nu_4\mu}|$ assuming $m_{\nu_4} = 100$ GeV, $m_{\tilde{l}_4} = 300$ GeV and $\lambda^{eff}_{442} = 0.05$. In Table IV we present observable values of $\lambda'^{eff}$ for $3\sigma$ observation at the LHC runs with $\sqrt{s} = 7$, 10 and 14 TeV.

The analysis shows that fourth family sleptons can be measured with $3\sigma$ significance having $10^{-3}$ for $\lambda'^{eff}$ and $10^{-2}$ for $|U_{\nu_4\mu}|$ at the LHC (14 TeV) with 100 fb$^{-1}$.

In conclusion, we have studied the resonance production of fourth family sleptons through R-parity violating couplings at the LHC energies, and it could be the first manifestation of the MSSM4 at the LHC.

Table III: The same as for Table 2 but for $\sqrt{s} = 14$ TeV

| | $\lambda'^{eff}_{411}$ | $\lambda'^{eff}_{412}$ | $\lambda'^{eff}_{421}$ | $\lambda'^{eff}_{413}$ | $\lambda'^{eff}_{422}$ | $\lambda'^{eff}_{423}$ | $\lambda'^{eff}_{4jk}$ |
|---|---|---|---|---|---|---|---|
| $\sigma_S(pb)$ | 0.36 | 0.29 | 0.061 | 0.177 | 0.042 | 0.02 | 0.96 |
| $S/\sqrt{B}$ | 350 | 290 | 60 | 175 | 41.4 | 19.7 | 946 |
| $L_{int}(pb^{-1})$ for $3\sigma$ | 7.23 | 10.7 | 247 | 30 | 525 | 2.3x$10^3$ | 1 |

Table IV: Achievable value of $\lambda'^{eff}$ for $3\sigma$ observation.

| $\|U_{\nu_4\mu}\|$ | $\sqrt{s} = 7$ TeV, $L_{int} = 1\,fb^{-1}$ | $\sqrt{s} = 10$ TeV, $L_{int} = 100\,fb^{-1}$ | $\sqrt{s} = 14$ TeV, $L_{int} = 100\,fb^{-1}$ |
|---|---|---|---|
| 0.1 | 0.017 | 0.0048 | 0.0040 |
| 0.05 | 0.010 | 0.0032 | 0.0028 |
| 0.01 | 0.0045 | 0.0015 | 0.0012 |

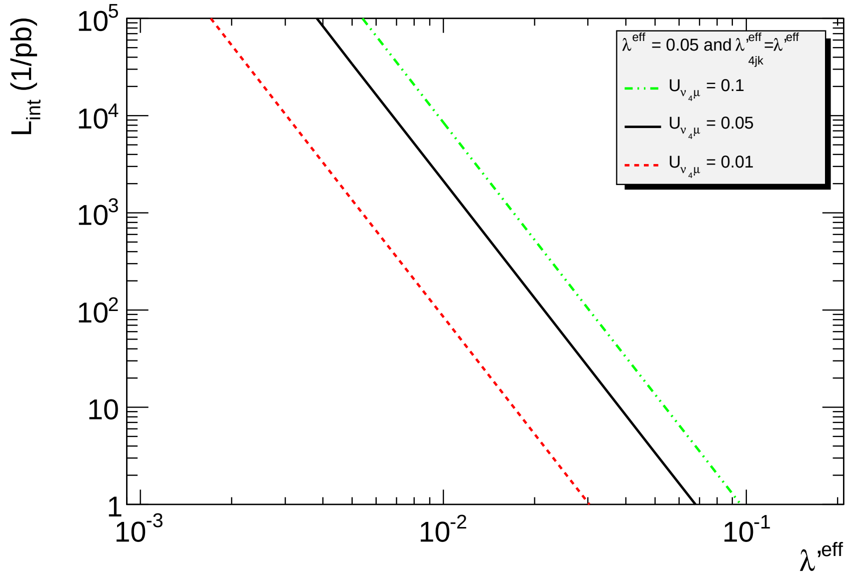



Figure 2: Integrated luminosity versus $\lambda'^{eff}$ for $3\sigma$ significance at $\sqrt{s} = 7$ TeV.


**Acknowledgments**

This work is partially supported by Turkish Atomic Energy Authority (TAEK) and State Planning Organization (DPT).



[1] M. Sahin, S. Sultansoy, S. Turkoz, Phys. Rev. D **83**, 054022 (2011).

[2] M. Maltoni *et al.*, Phys. Lett. B **476**, 107 (2000).

[3] H.J. He, N. Polonsky, S. Su, Phys. Rev. D **64**, 053004 (2001).

[4] G. Kribs *et al.*, Phys. Rev. D **76**, 075016 (2007).

[5] M. Bobrowski *et al.*, Phys. Rev. D **79**, 113006 (2009).

[6] M. S. Chanowitz, Phys. Rev. D **79**, 113008 (2009).

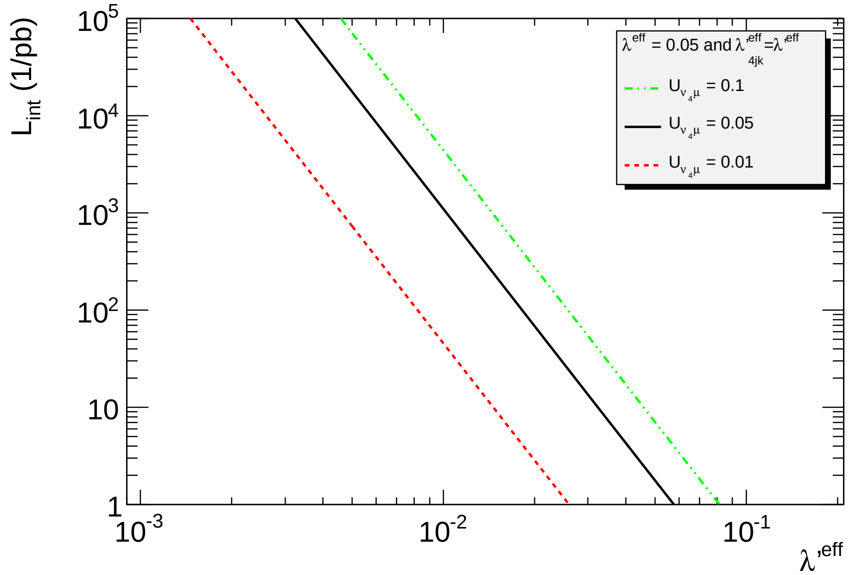



Figure 3: Integrated luminosity versus $\lambda'^{eff}$ for $3\sigma$ significance at $\sqrt{s} = 10$ TeV.

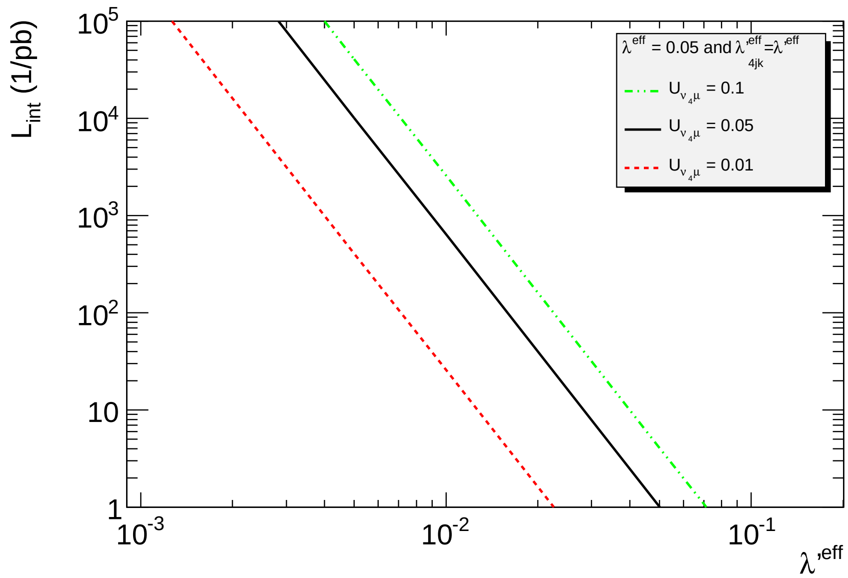



Figure 4: Integrated luminosity versus $\lambda'^{eff}$ for $3\sigma$ significance at $\sqrt{s} = 14$ TeV.


[7] A.K. Alok, A.Dighe, D. London, arXiv: 1011.2634 [hep-ph], (2010).

[8] M.S. Chanowitz, Phys. Rev. D **82**, 035018 (2010).

[9] J. Erler, P. Langacker, Phys. Rev. Lett. **105**, 031801 (2010).

[10] O. Eberhardt, A. Lenz, J. Rohrwild, Phys. Rev. D **82**, 095006 (2010).

[11] O. Cobanoglu *et al.*, arXiv:1005.2784 [hep-ph], (2010).

[12] J. Conway *et al.*, CDF Collaboration, CDF Note 10110.

[13] T. Aaltonen *et al.*, CDF Collaboration, arXiv:0912.1057 [hep-ex].

[14] K. Nakamura *et al.*, (Particle Data Group), Journal of Physics G **37**, 075021 (2010).

[15] M.S. Chanowitz, M.A. Furman, I. Hinchliffe, Phys. Lett. B **78**, 285 (1978); Nucl. Phys. B **153**, 402 (1979).

[16] M. S. Carena *et al.*, Nucl. Phys. B **472**, 55 (1996).

[17] V.Ari *et al.*, Europhys. Lett. **94**, 21001 (2011).

[18] R. Barbier *et al.*, Phys. Rep. **420**, 1 (2005).

[19] A. Bartl *et al.*, Z. Phys. C **76,** 549 (1997).

[20] E.Boos *et al.*, Nucl. Instrum. Meth. A. **534**, 250 (2004); arXiv:hep-ph/0403113 (2004).

[21] J. Pumplin *et al.*, JHEP **0207**, 012 (2002).

[22] H. Lacker, A. Menzel, JHEP **07**, 006 (2010), arXiv:1003.4532 [hep-ph], (2010).

[23] A.K. Ciftci, R. Ciftci, S. Sultansoy, Phys. Rev. D **72**, 053006 (2005).